Optimized Ionizing Radiation Detector for Measuring Average Density of Solid Particles in Airflow under Extreme Conditions

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Abstract: *During the operation of various air-conducting systems such as ventilation networks, gas pipelines, and aircraft gas-turbine engine air intakes in contaminated environments, solid components such as dust, sand, hail, and volcanic ash are often entrained in the airflow. To mitigate their negative effects, it is essential to identify these particles and periodically determine their mass flow relative to allowable threshold values. A prerequisite for this is the measurement of the average density of solid particles suspended in the airflow.*
This measurement can be performed using a variety of methods, including radioisotopic, ultrasonic, optical, and ionizing radiation techniques. The present study reports results on the use of ionizing radiation for measuring the average density of various solid particles in a two-component airflow (air + solid particles). First, the technical characteristics and operational conditions, including extreme conditions of different air-conducting systems are determined. Based on these factors, appropriate ionizing radiation sources and modern, optimized detectors are selected to enable accurate and reliable measurements.

Key Words: *Air-ducting device, solid particles, ionizing radiation detector, X-ray and gamma detection, density measurement.*

Introduction

In the operation of various air-transport systems, such as ventilation networks, gas pipelines, and air intakes of aircraft gas-turbine engines, solid components, including dust, sand, hail and volcanic ash, are often entrained in the airflow [1]. To mitigate their negative effects, it is essential to identify these particles and periodically determine their mass flow rates relative to permissible threshold values. A key prerequisite for this is the measurement of the average density of solid particles suspended in airflow [2].

Several approaches can be applied for this purpose, including radio frequency, ultrasonic, optical, and ionizing radiation techniques [3].

This paper presents the results of research on the application of ionizing radiation for measuring the average density of solid particles in a two-component airflow (air + solid particles).

Main Part

Air-ducting devices, have different designs and distinct geometric and physical characteristics depending on their purpose and operating conditions (see Fig. 1). Similarly, airflow and solid particles entrained within it exhibit specific properties that vary according to the type of air-conducting system.

Solid particles can enter air-conducting systems in different ways, depending on the operating environment and conditions of a particular system, as well as the airflow velocity and its ability to entrain ambient particles (Fig. 1).

Fig. 1 Example of dust entrainment in the air intake of an aircraft gas-turbine engine

Air-conducting systems operate in various environments under different operational and climatic conditions. The relevant characteristics are summarized in Table 1.

Table 1. Air/natural gas density, airflow velocity at the system inlet, and mass flow rate

#	Air-Conducting System	Air/Natural Gas Density	Air/Gas Velocity	Air/Gas Mass Flow Rate
1	Ventilation Duct	1.20–1.25 kg/m³ (air, 20 °C, 1 atm)	10–15 m/s (main duct); 5–10 m/s (branches)	0.5–2.0 kg/s (typical HVAC main ducts)
2	Gas Pipeline	0.7–0.9 kg/m³	10–25 m/s (main line); 5–15 m/s (branches)	0.05–0.5 kg/s (depending on pressure and diameter)
3	Aircraft Engine Air Intake	1.0–1.3 kg/m³ (sea level to 10 km altitude)	50–100 m/s (idle or taxi, medium revolutions); 150–250 m/s (takeoff)	300–400 kg/s (B737, CFM56); ≈50–100 kg/s (business jet)

In addition to the aforementioned factors, solid particles in air-conducting systems vary in their size, shape, and composition. Their concentrations in airflow or natural gas streams differ under various conditions [4]. Accordingly, the parameters of these particles play an important role in determining the average density of mixed flow. The parameters are summarized in Table 2.

Table 2. Characteristics of solid particles in air-conducting systems

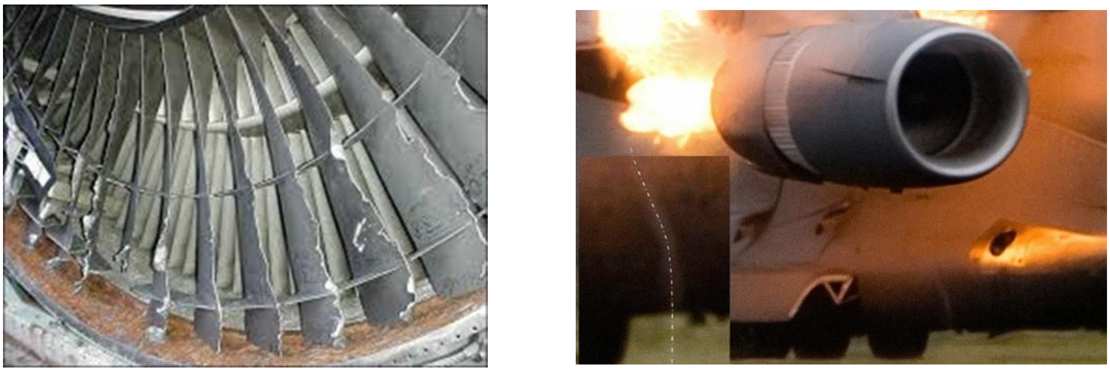
#	Air-Conducting System	Dust Particles	Sand Particles
1	Ventilation Duct	Size: 1–100 μm; Mass flow: 0.01–0.05 kg/s	Rare; Size: 100–300 μm; Mass flow: < 0.01 kg/s
2	Gas Pipeline	Size: 10–200 μm; Mass flow: 0.05–0.2 kg/s	Size: 200–500 μm; Mass flow: 0.02–0.1 kg/s
3	Aircraft Engine Air Intake	Size: 1–100 μm; Mass flow: 0.01–0.05 kg/s	Size: 100–600 μm; Mass flow: 0.05–0.15 kg/s

Naturally, the question arises: what potential damage can solid particles suspended in the airflow cause to the air-conducting system itself or to the components supplied with air or gas?

Therefore, it can be concluded that solid particles suspended in air or gas are unlikely to cause significant damage to ventilation ducts or gas pipeline airways over extended periods. However, this is not the case for the components and environments to which air or gas is delivered. Therefore, it is essential to periodically quantify the concentration of solid particles in the airflow or gas stream and compare the results with the permissible limits throughout the operational life of the air-conducting system.

Solid particles, particularly sand, can cause considerable damage and, consequently, material and technical losses when they penetrate hazardous zones of aircraft engines through the air intake. Sand particles first strike the fan blades of the engine, causing mechanical damage (Fig. 2a). After passing through the fan zone, sand enters the high-temperature regions of the engine, such as the turbine, where air temperatures range from 1,200°C to 1,600°C, while the melting point of quartz sand is approximately 1,710°C. In these regions, thermal processes occur, including sand heating, melting, and adhesion to walls, which adversely affect engine performance.

Additionally, in the reactive zones of the engine, chemical transformations and thermomechanical effects occur, including melting, sticking, and damage to the thermal barriers in the turbine. Compressor components may experience erosion, particles can accumulate or stick in the combustion chamber, and there is even the potential for fire initiation (Fig. 2b) [5].



a) b)

Fig. 2 Examples of the effects of solid particles in air on engine components

Therefore, the most significant and relevant concern among the discussed air-conducting systems is the automated assessment and control of solid particles suspended in the airflow to prevent reductions in the operational life of an aircraft gas-turbine engine.

Several studies [2,6] have addressed solutions to this problem, providing general concepts and methods, including recommendations for using ionizing sources to measure the mass flow of solid particles in the airflow entering an aircraft engine's air intake.

To implement the authors' recommendations in practice, it is necessary to correctly select the type and parameters of the ionizing radiation source and the corresponding detector for the extreme conditions in which the aircraft engine operates: ambient temperature range of –60°C to +50°C; air density, inlet velocity, and mass flow in the air-conducting system, as presented in Table 2; and information on dust and other solid particles in the airflow, as given in Table 2. The dimensions of the air intake (Table 1) must also be considered. [7]

Given these constraints, only specific types and parameters of gamma radiation or X-rays can be employed. Alpha and beta radiations were excluded because they are completely absorbed under these conditions and cannot provide the necessary measurement information.

Among gamma-emitting radioisotope sources, the most commonly used practical sources are summarized in Table 3.

Table 3. Properties of ^{60}Co, ^{137}Cs, ^{241}Am

#	Source Name	Half-Life (years)	Radiation Energy (keV)	Absorption Coefficient Quartz (SiO_2, ρ≈2.65 g·cm^{-3}) μ (cm^{-1})
1	Cobalt-60	5.2714	1173, 1332	$\sim(0.07 - 0.12)\ cm^{-1}$
2	Cesium-137	30.04	662	$\sim(0.10 - 0.25)\ cm^{-1}$
3	Americium-241	432.6 ± 0.6	59.5	$\sim(1.0 - 3.0)\ cm^{-1}$

Based on the absorption coefficients of the radioisotope sources presented in the table, and considering that the concentration of foreign particles mixed in the air stream entering the air turbine engine is sufficiently low (mass flow rate not exceeding 0.05-0.15 kg/s), the task is best solved using americium-241, since its absorption coefficient significantly exceeds that of the others. The energy of ^{241}Am gamma radiation (59.5 keV) provides sufficient penetration to detect particles in an air stream. In addition, its long half-life (~ 432 years) ensures stable operation over a long period, making it practical for continuous monitoring [8].

As an alternative to radioisotope sources, X-ray sources can be used, provided that a specific portion of the emitted spectrum is selected to optimize the particle detection. Typical X-ray sources include tungsten (20–120 keV), molybdenum (17–20 keV), and copper (8–10 keV) targets. The choice of source depends on the desired penetration depth, particle size, and absorption characteristics, with higher energy X-rays (e.g., tungsten) being more suitable for relatively large air inlet systems and higher airflow densities, whereas lower energy X-rays (e.g., copper or molybdenum) can be used for compact or low-density systems. The absorption coefficients of quartz, which represent typical dust and sand particles, range from approximately 1 cm^{-1} (tungsten) to 7–8 cm^{-1} (copper), allowing for the appropriate calibration of the detector system. By carefully selecting the radiation source and matching it to the detector parameters, accurate real-time measurements of the mass flow of solid particles under extreme operating conditions in aircraft gas turbine engines can be achieved, thereby enabling the preventive monitoring and protection of critical engine components. The types of X-ray sources that are likely to be used are presented in Table 4. [9,10]

Table 4. Properties of X-rays Tubes

#	Source / target	Typical spectrum / characteristic energies (keV)	Approx. linear attenuation μ (cm^{-1}) for quartz (SiO_2, ρ≈2.65 g·cm^{-3})
1	Tungsten (W) target (X-tube)	Bremsstrahlung 20–120 keV; W characteristic ~59, 67 keV	**~0.3 – 1.5 cm^{-1}** (decreasing with energy; ~0.5–1.0 near 60 keV).
2	Molybdenum (Mo) target (X-tube)	Kα ≈ 17.5 keV, Kβ ≈ 19.6 keV	~ **2.5 – 8 cm^{-1}** (strong photoelectric region; expect a few cm^{-1} at 17–20 keV).
3	Copper (Cu) target (X-tube)	Kα ≈ 8.05 keV, Kβ ≈ 8.9 keV	~ **50 – 110 cm^{-1}** (very high at ~8 keV because of photoelectric effect).
4	Iron (Fe) target	Kα ≈ 6.40 keV	~ **100 – 300 cm^{-1}** (very large — low-keV X-rays are strongly absorbed in SiO_2).
5	Silver (Ag) target	Kα ≈ 22.1 keV, Kβ ≈ 24.9 keV	~ **1.5 – 5 cm^{-1}** (lower than Mo/Cu region but still photoelectric-influenced).

This measurement can be performed using multiple methods, including radioisotope gamma sources, X-rays, ultrasonic, and optical techniques. In this study, we focused on the use of ionizing radiation to measure the average density of solid particles in a two-component airflow (air + particles) [11]. The technical characteristics and operational conditions of the duct systems, including extreme scenarios, were analyzed to select appropriate radiation sources and detectors with optimal modern specifications.

The choice of detector and photon energy is critical and involves trade-offs between sensitivity and penetration. Low-keV X-ray tubes (e.g., Cu, Fe, and Mo targets) provide high sensitivity for detecting small particle concentrations but are limited in penetration, requiring thin windows and careful calibration. Medium-energy sources (e.g., W-target X-ray tubes or Am-241, ~ 60 keV) offer a compromise, enabling the measurement of moderate-to dense-particle clouds while maintaining sufficient sensitivity. High-energy gamma sources (e.g., Cs-137 and Co-60) penetrate dense particle clouds and heterogeneous mixtures but exhibit lower sensitivity to small density variations and require larger, highly sensitive detectors with radiation safety precautions [12].

Considering these trade-offs, this study identifies the optimal radiation sources and detector types for the quantitative, real-time measurement of particle density in airflow under extreme environmental conditions, supporting both monitoring and preventative maintenance in industrial and aerospace systems [13].

Extreme environments, high-density dust, and volcanic plumes, where low-energy X-rays are completely absorbed [12].

Table 5. Summary Table: Detector Type Tradeoffs for Airflow Particle Density Measurement

#	Source / Energy	Sensitivity to low particle density	Penetration through dense clouds	Detector considerations	Typical application
1	Low-keV X-ray tube (Cu, Fe, Mo)	High	Low	Thin-window detectors, low-energy filters	Clean/moderately polluted airflows
2	Medium-energy X-ray tube / Am-241 (~60 keV)	Moderate	Moderate	Standard detectors, moderate shielding	Industrial airflow, moderate dust levels
3	High-energy gamma (Cs-137, Co-60)	Low	High	Scintillators or HPGe, strict radiation safety	Dense, extreme dust clouds, volcanic/industrial plumes

Detector Selection for Airflow Particle Density Measurement

The measurement of the average density of solid particles in airflow under extreme environmental conditions requires careful selection of radiation detectors, as their performance depends strongly on the photon energy, sensitivity, and penetration capabilities. The technical goal is to detect and quantify dispersed particles, such as dust, sand, volcanic ash, or hail, in real time, even in high-velocity or heavily contaminated airflows [13-15].

1. **Gas-filled detectors (Ionization chambers, Proportional counters, Geiger-Müller tubes)**
   - **Strengths:** Broad energy response, simple construction, robustness in harsh environments and ability to handle moderate to high fluxes.

   - **Limitations:** Low energy resolution; insufficient sensitivity for detecting small density variations in low particle-concentration airflows.
   - **Application:** Suitable when **medium-energy photons (~ 30–100 keV) or gamma rays** are used, providing reliable average particle density measurements over large airflow volumes.
2. **Scintillation detectors (NaI (Tl), CsI (Tl), plastic scintillators)**
   - **Strengths:** High detection efficiency and moderate energy resolution; capable of measuring low-energy X-rays and medium-energy gamma-photons. A fast response allows **real-time monitoring**.
   - **Limitations:** Sensitive to temperature and mechanical vibration; some scintillators require shielding from background radiation.
   - **Application:** Ideal for **low - to moderate particle densities**, where small changes in transmitted photon intensity must be resolved accurately, such as in clean or moderately polluted airflows.
3. **Semiconductor detectors (Silicon PIN diodes, HPGe, CdTe, CZT)**
   - **Strengths:** Excellent energy resolution and high sensitivity to low-keV photons (X-rays), enabling precise particle density measurements. It is compact and suitable for integration into flow channels.
   - **Limitations:** HPGe requires cryogenic cooling, whereas CdTe and CZT are more robust but limited in size. High-energy gamma detection may require thicker or stacked crystal detectors.
   - **Application:** Highly suitable for **low-keV X-ray detection**, where precise density measurements of fine particles are required, such as in low-concentration airflows or laboratory-scale experiments.

The choice of detector type is critical for solving key technical problems [16]:

- **Sensitivity versus penetration:** Low-keV detectors (semiconductors, scintillators) are highly sensitive to small particles but cannot penetrate dense clouds. High-energy gamma detectors penetrate thick flows but require high-efficiency or large-volume sensors.
- **Real-time monitoring:** Scintillation and semiconductor detectors provide fast response times, allowing dynamic measurement of particle density in moving airflows.
- **Robustness under extreme conditions:** Gas-filled detectors and solid-state detectors (CdTe, CZT) are durable under high airflow rates, vibration, and temperature fluctuations, suitable for industrial or aerospace environments.
- **Calibration flexibility:** Semiconductor and scintillation detectors allow precise energy discrimination, facilitating the calibration of specific particle compositions or mixtures.

Based on the above tradeoffs, the detectors most suitable for measuring the average solid particle density in airflow in this study were as follows [17,18]:

- **Semiconductor detectors (Si, CdTe, and CZT)** are used for low- to medium-energy X-ray measurements, where high sensitivity is required for small particle concentrations.

- **Scintillation detectors (NaI(Tl), CsI(Tl))** are used for medium-energy photons and moderate-density clouds, allowing fast, real-time monitoring.
- **Gas-filled detectors (ionization chambers, proportional counters)** are used for high-energy gamma radiation, dense particle clouds, or situations where robustness under extreme operational conditions is prioritized.

By integrating these detector types with appropriate photon energies, this study achieved a flexible, multi-scale measurement capability, from fine dust detection to monitoring dense, highly contaminated flows, providing a reliable solution to the technical challenges of particle density measurement in airflow systems [19].

Table 6. Recommended Detector Types Based on Photon Energy and Particle Density

#	Photon Energy Range	Sensitivity to Particle Density	Penetration in Dense Flow	Recommended Detector Type	Typical Application
1	6–20 keV	Very high (detects fine particles, low concentrations)	Low	Semiconductor (Si, CdTe, CZT)	Laboratory airflow, clean or moderately polluted air
2	20–60 keV	High	Moderate	Semiconductor + Scintillation (NaI (Tl), CsI (Tl))	Industrial airflow, moderate dust levels
3	60–100 keV	Moderate	Moderate	Scintillation (NaI (Tl), CsI (Tl)), Gas-filled	Industrial airflows, medium-density clouds
4	100–500 keV	Low	High	Gas-filled, Scintillation (high-efficiency), HPGe	Dense particle clouds, aerospace ducts
5	>500 keV (gamma rays, e.g., Cs-137, Co-60)	Very low	Very high	Gas-filled, large-volume Scintillation, HPGe	Extreme environments, volcanic or industrial plumes

By linking the photon energy, particle density sensitivity, and detector type, this framework enables flexible and optimized measurement strategies for airflow monitoring. Low-energy semiconductors are ideal for the high-resolution detection of fine particles, scintillators are optimal for moderate densities and real-time measurements, and gas-filled detectors are suitable for extreme or highly dense particle flows. This multiscale approach ensures reliable quantitative monitoring across a wide range of operational conditions.

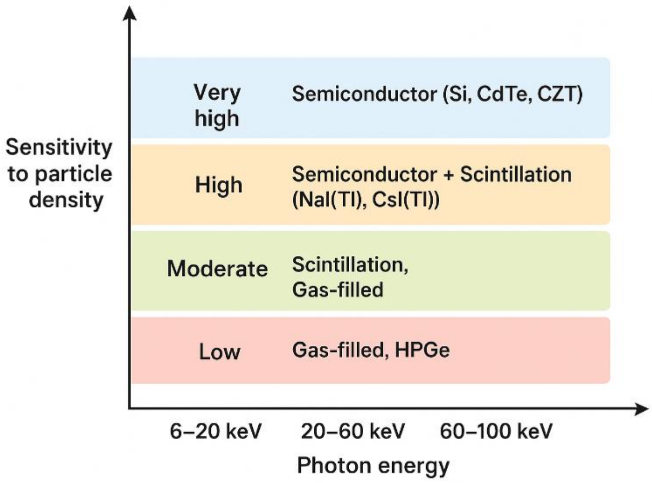


Fig. 3 Illustrating photon energy ranges, particle density sensitivity, and detector types

Conclusion

A systematic framework has been developed to assess the average density of solid particles in airflow under extreme conditions. By analysing airflow characteristics, particle properties, and environmental constraints, optimal combinations of ionizing radiation sources and detectors have been identified. Low-energy X-ray semiconductor detectors exhibit high sensitivity for detecting fine, low-concentration particles, while medium-energy X-ray and Am-241 sources with scintillation detectors are effective for moderate particle densities. High-energy gamma sources, when paired with gas-filled detectors, enable the monitoring of dense or highly contaminated flows.

This multiscale approach ensures precise, real-time quantification of particle density across diverse operational scenarios, thereby supporting preventive maintenance and safeguarding critical components in aerospace systems. The methodology provides a robust foundation for the automated monitoring of particle-laden airflows in harsh environments, enabling reliable long-term performance and risk mitigation.

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მაიონებელი გამოსხივების წყაროებისა და შესაბამისი დეტექტორების ოპტიმალური მახასიათებლების შერჩევა ჰაერის ნაკადში შერეული მყარი ნაწილაკების საშუალო სიმკვრივის გასაზომად ექსტრემალურ პირობებში

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რეზიუმე: *სხვადასხვა ჰაერსატარ მოწყობილობების - სავენტილაციო სისტემები, გაზსადენის მილები, თვითმფრინავი აირტურბინული ძრავების ჰაერმიმღებები და სხვა - დაბინძურებულ გარემოში ექსპლუატაციისას მათში გამავალ ჰაერის ნაკადში ხშირად ხდება ისეთი მყარი კომპონენტების შერევა, როგორიცაა: მტვერი, ქვიშა, სეტყვა, ვულკანური ფერფლი და სხვა. ამ კომპონენტების მოქმედების უარყოფითი გავლენის პრევენციისათვის საჭიროა მოხდეს მათი იდენტიფიცირება და მასური ხარჯის პერიოდული განსაზღვრა და შედარება ზღვრულ დასაშვებ მნიშვნელობასთან, რის განსახორციელებლად უპირველეს ყოვლისა უნდა გაიზომოს ჰაერის ნაკადში შერეული მყარი ნაწილაკების საშუალო სიმკვრივე.*

ამ უკანასკნელის გაზომვა შესაძლებელია სხვადასხვა მეთოდებით - რადიოსიხშირული, ულტრაბგერითი, ოპტიკური, მაიონებელი გამოსხივების გამოყენებით და სხვა.

სტატიაში წარმოდგენილია კვლევის შედეგები, რომლებიც ეხება მაიონებელი გამოსხივების გამოყენებას ორკომპონენტიან ჰაერის ნაკადში (ჰაერი+მყარი ნაწილაკები) შერეული სხვადასხვა მყარი ნაწილაკების საშუალო სიმკვრივის გაზომვისათვის. უპირველესად დადგენილია ჰაერსატარ მოწყობილობების ტექნიკური მახასიათებლები და საექსპლუატაციო პირობები, მათ შორის ექსტრემალური, და ამ უკანასკნელთა გათვალისწინებით შერჩეულია მაიონებელი გამოსხივების წყაროები და შესაბამისი თანამედროვე ოპტიმალური დეტექტორები.

საკვანძო სიტყვები: *ჰაერსატარი მილი, მყარი ნაწილაკები, გამა-გამოსხივება, რენტგენის გამოსხივება, სიმკვრივის გაზომვა.*